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**MAGNETIC SHIELDING  
OF  
INTERPLANETARY SPACECRAFT  
AGAINST  
SOLAR FLARE RADIATION**

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**NASA/USRA Advanced Design Program**

by

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### Abstract

This project is concerned with the design and engineering of deployed, high temperature superconducting coils (DHTSC) for the production of large volume, low-intensity magnetic fields to produce shielding of manned spacecraft against solar flare protons. The concept of using a superconducting coil for magnetic shielding against solar flare radiation during manned interplanetary missions has long been contemplated and was considered in detail in the years preceding the Apollo missions. Only lower temperature superconductors were then known, and the field coils needed to produce the protective field were limited in size to the ship dimensions. These coils were ineffective unless they carried enormous total circulating currents, and their potential use in the Apollo program was abandoned. With high temperature superconductors, it has now become realistic to consider deploying the field coils beyond the spacecraft hull and the current requirement is dramatically lowered together with the total system mass and energy requirements. Importantly, concomitant experiments are made possible with such a magnetic field generating system -- the interaction between the field of the earth and the field produced by the superconducting coil to obtain a thrust capable of increasing the mean orbital radius. With current high temperature superconductor materials, especially wires that have been produced within the last year, a test of all these concepts now appears possible through the use of a payload small enough to fly piggyback aboard another mission.

Working first with groups of three students, then with groups of up to seven students, engineering analyses of both the general requirements of magnetic shielding systems and the design of specific deployed systems have been carried out. The result of this effort supports the conclusion that not only are such deployed systems practical but that they also show dramatic weight and energy advantages compared to other shielding systems.

## Introduction

The ultimate objective of this work is to design, build, and fly a dual-purpose, piggyback payload whose function is to produce a large volume, low intensity magnetic field and to test the concept of using such a magnetic field (1) to protect spacecraft against solar flare protons, (2) to produce a thrust of sufficient magnitude to stabilize low satellite orbits against orbital decay from atmospheric drag, and (3) to test the magsail concept. These all appear to be capable of being tested using the same deployed high temperature superconducting coil. In certain orbits, high temperature superconducting wire, which has now been developed to the point where silver-sheathed high  $T_c$  wires one mil in diameter are commercially available, can be used to produce the magnetic moments required for shielding without requiring any mechanical cooling system. The potential benefits of this concept apply directly to both earth-orbital and interplanetary missions. The usefulness of a protective shield for manned missions needs scarcely to be emphasized. Similarly, the usefulness of increasing orbit perigee without expenditure of propellant is obvious. This payload would be a first step in assessing the true potential of large volume magnetic fields in the U.S. space program. The objective of this design research is to develop an innovative, prototype deployed high temperature superconducting coil (DHTSC) system.

## Historical Perspective

The concept of using superconducting coils to produce magnetic fields for protection from energetic particle radiation has been developed since the late 1950s. While contemplated as a means of providing radiation protection during manned missions beyond the magnetosphere, the concept gained interest in the early 1960s as a means of protecting satellites from nuclear blasts. On July 9, 1962, an explosion of a 1.4 megaton nuclear device 250 miles above Johnston Island (Project STARFISH) produced an artificial radiation belt with a peak radiation dose rate of approximately 120,000 rads per hour. This resulted in the loss of three satellites<sup>1</sup>, and produced significant concern over satellite protection technologies. This concern led to the production of a laboratory-based prototype system which relied on low-temperature superconductors, and the idea was further developed for manned space missions. Magnetic shielding was one radiation shielding concept seriously considered for the Apollo missions, although it was later abandoned. The use of magnetic field shielding for satellites has recently been reassessed for satellite shielding applications due to the advent of high temperature superconductors.<sup>2</sup> With renewed interest in manned missions to Mars, magnetic shielding appears to provide the required capabilities for proper crew shielding at significant energy savings over all other designs.

## **Radiation Issues for Manned Spaceflight**

Energetic space radiation is generally classified by three prime sources: radiation due to trapped particles in the Van Allen Belts, radiation in the form of galactic cosmic rays, and radiation due to solar particles emitted in flares, storms, and the solar wind. For interplanetary travelers, the particles that pose the greatest threat are those with high energy and fluxes. Galactic cosmic rays contain particles with the highest energies (typically greater than 1 GeV), followed by solar flare particles (10 to 1000 MeV), and finally Van Allen belt radiation. The former two forms of radiation pose potential exposures that dwarf the latter.

Historical data is commonly used to predict potential exposures, and the benchmark solar flares most often cited occurred in February of 1956, November of 1960, and August of 1972. While these flares are among the most powerful ever recorded, their magnitudes are not unique. In fact, a flare of the same order of magnitude as the August 1972 event was recorded in October 1989.<sup>3</sup> The unshielded blood-forming-organ (BFO) dose equivalents for the three events were 62 rem, 110 rem, and 411 rem respectively.<sup>3</sup> The BFO dose equivalents were 31.5 rem, 39.8 rem, and 50.7 rem respectively even with a 10 grams per square centimeter shield.<sup>4</sup> Since the recommended rem limit for vital organs over a 30 day period for astronauts is 25 rem, and is placed at 50 rem annually<sup>5</sup>, significant concern must be raised for any long duration space missions. While current U.S. manned missions benefit from the natural protection afforded by the Earth's magnetosphere, interplanetary missions will require specific attention to shielding in spacecraft design. The solar cycle is a period of 11 years, and it has been noted that extremely large flares occur once or twice per cycle with lesser flares occurring every few weeks.<sup>6</sup>

While the Apollo missions were successfully planned to avoid periods of high solar flare activity, this will not be possible for manned Mars missions, which will last several years. In addition, the unpredictability of large solar flares forces mission designers to consider worst case scenarios for potential exposure levels. Finally, it should be recognized that the cumulative effects of smaller flares will be quite significant as well. If normal levels of solar flare activity are assumed, it has been predicted that an unprotected crew would receive an annual dose of 100 rem per year on a Mars mission.<sup>7</sup>

### **Mass Shielding**

Mass shielding is generally referred to as a passive shielding concept. Simply, bulk forms of matter have inherent shielding capabilities. The major problem encountered with mass shielding is that the required shield thickness increases precipitously as the energy of the particles to be protected from increases. Furthermore, the production of energetic secondaries as a result of energetic particles interacting with the shielding material must be considered, and it should be noted that the level of

production of secondary particles such as gamma rays, protons, and neutrons, is a function of the type of shielding material, and specifically increases with increasing atomic number.<sup>8</sup> For a Mars mission, however, the various mass shielding concepts that have been suggested all suffer from the disadvantage of being inherently too heavy for practical implementation. This is especially the case if the most penetrating of the solar flare radiation is to be stopped. Thus, while the structural configuration of a spacecraft provides inherent shielding, additional shielding strategies must be considered in order to achieve reasonable mass levels.

### **Alternative Shielding Strategies**

A number of active shielding concepts have been suggested, including electric, magnetic, and plasma shielding. Of these, both the electric and plasma shielding strategies suffer from severe technical problems which render their implementation infeasible. Thus, magnetic shielding, which simply involves creating a magnetic field around a spacecraft and thus deflecting charged particles, appears to be the greatest hope for use as an active shield.

### **Magnetic Shielding**

Work on the magnetic shielding concept was initiated before manned spaceflight was even realized.<sup>9,10,11</sup> Original development of the concept was, of course, limited to low temperature superconductors, at liquid helium temperatures. The use of such low temperature superconductors posed a daunting set of problems. First, even with the equilibrium temperatures attained by a spaceship in outer space, cooling to liquid helium temperatures would still be needed through mechanical refrigeration techniques in order to achieve the superconducting state. This requirement alone limited magnetic shielding designs to the use of ship-board coils<sup>12</sup>, especially due to the power requirements for maintaining the cryogenic temperature<sup>13</sup>. Second, ship-board coils required high magnetic field intensities only achievable through extremely high currents in order to shield a reasonably high volume. Third, the masses of the coils and the related supporting structures required for such coils brought into question any gains in savings over mass shielding techniques.<sup>12,14,15</sup> It was found that a weight-savings was achieved when protecting against 1 bev or higher protons, and that the structural support of the shield was the main component of the total mass of the system.<sup>16</sup>

One additional concern noted with magnetic shields is the effects that such high magnetic fields might have on living organisms, especially due to long-term exposures. Studies have been undertaken as to the potential dangers to space travelers<sup>17</sup>, but no opinion has won general acceptance even today.

The debate on the general topic of magnetic field interactions with living organisms still can be seen especially seen with respect to the high voltage electrical lines that are used to supply power across the country. However, with proper design the field present in the crew quarters can be reduced to values lower than normally present on earth.

With the advent of high temperature superconductors, heightened interest in magnetic shields is apparent. This interest is further fueled by recent planning for a manned mission to Mars which would directly benefit from the development of magnetic shielding technologies. A number of studies have focused on the use of the new ceramic materials which can achieve superconductivity at liquid nitrogen temperatures as well as on possible configurations for a magnetic shield. One such configuration is that of a deployed torus.<sup>12</sup> These new superconducting materials present a number of notable advantages, including significantly less cooling needs as well as deployed configurations for superconducting wires. The deployed configuration appears especially promising due to enormous reductions in mass and energy requirements over previous ship-board coil designs. In addition, the danger that catastrophic failure of the magnetic shield poses to a spaceship's crew is minimized by deploying the shield away from the ship as opposed to producing the necessary magnetic fields with a ship-board coil.<sup>12</sup>

### Mathematical Basis for the Design

The concept of using deployed high temperature superconducting coils for producing magnetic fields has been developed by several investigators<sup>12,18</sup>, and it is instructive to examine the basic principles behind this concept. First, it is important to establish the desired characteristics of the shield. In a practical full sized scenario, it is desired to fully protect an area of a spaceship of 10 meters radius. With the constraint of establishing the maximum level of energetic particles, the necessary magnetic field strength can be calculated once the protected dimension is determined. This dimension,  $C_{st}$ , known as the Störmer radius, has been shown to measure the magnetically protected region<sup>19</sup>, although complete protection is only achieved in approximately 40% of that characteristic length<sup>9</sup>. This dimension, measured in meters, is determined as follows<sup>20</sup>:

$$C_{st} = \sqrt{\frac{q\mu_o M}{4\pi P}} \quad (1)$$

where     $q$     =    the particle charge  
            $\mu_o$  =    the permittivity of free space  
                  =     $4\pi \times 10^{-7}$  H/m  
            $P$     =    relativistic particle momentum



The magnetic moment, M, can be calculated using the relation

$$M = NIA \quad (2)$$

for which N = the number of turns in the loop

I = the current in each turn

A = the area enclosed by the loops  
forming the coil

Now, momentum is calculated as the product of the mass and the velocity of an object. However, in the case of basic particles, relativistic considerations must be made. Thus, in the case of particles approaching the speed of light, the momentum is calculated as follows:

$$P = \frac{m_0 v}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} \quad (3)$$

where  $m_0$  = the particle rest mass

v = the particle velocity

c = the speed of light

=  $3 \times 10^8$  m/s

The calculation of momentum as achieved using equation 3 may also be achieved using the relativistic relation in equation 4:

$$\gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}} \quad (4)$$

Equation 4 is simply the ratio of the actual energy of the particle in question to the rest energy of that particle, as simplified in equation 5:

$$\gamma = \text{Actual Energy} / \text{Rest Energy} \quad (5)$$

In the specific case of interest, if it is desired to fully protect a radius of 10 meters, then the Störmer radius will need to be approximately 25 meters. The magnetic moment may be calculated from

equation 1. A cutoff energy of 200 MeV has been suggested<sup>21</sup>, and to protect a Störmer radius of 25 meters from protons of this energy, the relativistic momentum must be found. Knowing that 1 MeV is equivalent to  $1.6 \times 10^{-13}$  joules, the kinetic energy of 200 MeV protons can be used to determine the velocity of those protons. This is achieved through solving the following:

$$K.E. = mc^2 - m_0c^2 \quad (6)$$

Here,  $m_0$  is the mass of the proton which is  $1.66 \times 10^{-27}$  kg. Thus, using equation 6 with  $3.2 \times 10^{-11}$  joules of kinetic energy, a proton is traveling at a speed of  $1.7 \times 10^8$  m/sec (approximately 57% the speed of light). The momentum of the proton can then be found using equation 3, and is determined to be about  $3.6 \times 10^{-19}$  kg-m/sec. Using equation 1, the magnetic moment for protection against these particles is thus found to be nearly  $1.4 \times 10^{10}$  ampere-turns  $\cdot$  m<sup>2</sup>.

Now, the case of a ship-board coil versus deployed coils can be examined in greater detail. In particular, since the magnetic moment increases as the area enclosed by the coil it is immediately seen that the needed current,  $I$ , for a single turn coil will decrease with the radius of the coil. To obtain the dependence of the total stored electrical energy needed to activate the shield as a function of the radius of the torus, one can solve for the total current using equation 1, to give:

$$I = \frac{4\pi C_{st}^2 P}{q\mu_0 A} \quad (7)$$

Equation 7 may be solved, for example, for 200 MeV protons to approximate the current in amperes as a function of radius as :

$$I = \frac{4.5 \times 10^9}{R^2} \quad (8)$$

Here, it is interesting and important to note a relation which determines the energy required for magnetic shielding.

The energy stored in the system,  $E$ , is given by

$$E = \frac{1}{2} LI^2 \quad (9)$$

where  $L$  = the coil inductance.

If equation 7 is substituted into equation 9, and if the inductance is assumed to be a constant, then an expression for energy as a function of radius is obtained:

$$E = \frac{1}{2} L \left( \frac{4\pi C_{st}^2 P}{q\mu_o A} \right)^2 \quad (10)$$

For the example that we have here considered (200 MeV protons,  $C_{st}$  of 25 meters), equation 8 can be substituted into equation 9 to yield:

$$E = \frac{1}{2} L \frac{(2 \times 10^{19})}{R^4} \quad (11)$$

While it should be realized that this equation, of course, varies with the energy of the particles as well as with the desired Störmer radius, the important result shown is the dependence on the radius to the minus fourth power. This shows that the smaller the radius and consequently the smaller the torus, the larger the energy required by a massive factor. This is especially relevant when considering deployed coils of much larger size, since likewise the bigger the radius and consequently the bigger the torus, the smaller the energy requirement for protecting from the same energetic particles, again by a fourth power dependence.

### Torus Mass Optimization

The torus size and mass can be optimized with knowledge of the total mass as a function of the radius of the torus. First, it should be realized that the total mass (TM) is simply the sum of the wire mass (MW) and torus-tube mass (MT):

$$M_{TOT} = M_w + M_T \quad (12)$$

The wire mass is determined as follows:

$$M_w = 2\pi R a \rho \quad (13)$$

where R = torus radius  
a = total cross sectional area of wire  
= ratio of the current to the total current density

$\rho$  = superconductor wire density

The torus-tube mass is found as follows:

$$M_T = 2\pi Rm \quad (14)$$

where  $m$  = the mass of the torus per unit length.

The optimum size in terms of the radius is finally determined by differentiating the total mass with respect to the torus radius, and then setting this to zero.

With the above procedure and previously calculated results, it is possible to now optimize the size and mass of the torus for particular constraints. First, it is assumed that the mass of the tube which forms the desired torus is 87 g/m, which is based upon the estimated total surface area required for Mylar. Assuming protection of a Störmer radius of 25 meters, equation 8 can be used to perform the optimization. Further constraints on the capabilities of the superconductor wire must be established and these can be based on recent reported properties of high temperature superconductor wire. It is claimed that a current density of 108 amps/m<sup>2</sup> can be achieved<sup>22</sup>, with a wire density of approximately 8 g/cm<sup>3</sup>. Now, if it is still desired to protect from 200 MeV protons, then the total mass can be found to be the sum of the superconductor wire mass and the torus mass using the above results.

Knowing that the critical current in a wire is simply the ratio of the current to the cross sectional area (a) of that wire, the cross-sectional area can be computed as a function of radius. Thus, using equation 8, the following approximation results:

$$a = \frac{45}{R^2} \quad (15)$$

The mass of the wire may then be calculated by simply multiplying the circumference of the wire by the cross-sectional area and the density of the wire. This results in the following:

$$M_w = 2\pi R a \rho = \frac{2.3 \times 10^6}{R} \quad (16)$$

Next, the mass of the torus-tube must be calculated, and this is found similarly as the product of the circumference and the mass of that tube per meter:

$$M_T = 2\pi R \left( 0.09 \cdot \frac{kg}{m^3} \right) = 0.55R \quad (17)$$

Thus the total mass, being the sum of the wire mass and tube mass, is simply:

$$M_{TOT} = \frac{2.3 \times 10^6}{R} + 0.55R \quad (18)$$

To find the optimum size, equation 18 can be differentiated with respect to the radius and set equal to zero as follows:

$$\frac{dM_{TOT}}{dR} = \frac{2.3 \times 10^6}{R^2} + 0.55 = 0 \quad (19)$$

Solving this equation yields an optimum radius of 2036 meters. The optimum mass is then found using equation 18 to be 2240 kg for the full size (not prototype) system. It should be noted that the weight of the wire is equal to the weight of the tube in the optimum case. This problem can be easily repeated for any assumed Störmer radius, proton energy, or tube mass per unit length.

### Calculation of Force and Stress in Coils

The forces and stresses involved in a deployed coil system. These characteristics may be calculated as follows. First, the magnetic force in a single wire coil may be determined from the following relation<sup>23</sup>:

$$F_{MAG} = \frac{\mu_o I^2}{4\pi} \left[ \ln\left(\frac{8R}{r}\right) - \frac{3}{4} \right] \quad (20)$$

where     R   =   the coil radius  
               r   =   the wire radius  
                $\mu_o$  =   the permittivity of free space  
                      =    $4\pi \times 10^{-7}$  H/m  
               I   =   the current

The wire radius must be calculated, and this is achieved once again by realizing that the area of the wire is equal to the ratio of the current (I) to the critical current density (J). Thus, the wire radius is determined using the following relation:

$$r = \sqrt{\frac{I}{\pi J}} \quad (21)$$

As an example, if the required current is 1093 amps as calculated above and the critical current density is  $10^8$  amps/m<sup>2</sup>, a required wire radius of  $1.87 \times 10^{-3}$  meter is found. This allows the magnetic force to be determined from equation 20, and this value is found to be 1.82 newtons, which is very low. The stress is simply the ratio of the force to the area, as is shown below:

$$\sigma = \frac{F_{MAG}}{\pi r^2} \quad (22)$$

Using equation 22, a stress of  $1.66 \times 10^5$  N/m<sup>2</sup> is found.

The stress in terms of the Störmer radius and the coil radius can be calculated by combining equations 1, 20, and 22, to obtain the following relation:

$$\sigma = \frac{JC_{st}^2 P}{\pi q R^2} \left[ \ln\left(\frac{8R}{r}\right) - \frac{3}{4} \right] \quad (23)$$

As an approximation, it can be seen from equation 23 that the stress increases as a function of the square of the Störmer radius and decreases as a function of the square of the torus radius, neglecting the  $\ln R$  term. All of these calculations can be repeated for any chosen particle energy and Störmer radius.

### Selective Emitter Calculations

With the planned use of superconducting wire, the equilibrium temperature attained by the wire in the currently envisioned deployed state<sup>12</sup> suggests the necessity of supplemental cooling. This is due to the fact that the superconducting conditions require temperatures below the equilibrium temperature. Even by using selective absorber and emitter coatings with an absorptivity to emissivity ratio of  $6.17 \times 10^{-2}$ , achievable with glass films with an internal reflecting layer of silver, the equilibrium temperature attained is still 147°K.<sup>12</sup> This assumes that the coil consists of 1 wire oriented with its major length perpendicular to the sun. Of course, this is well above the transition temperature of the known high temperature superconducting materials.

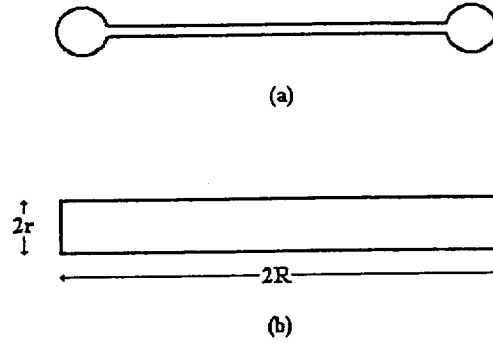


Fig. 1 Torus geometry shown in (a) cross section and (b) area projection (Note: not to scale, the sunlight is parallel to the plane of the torus)

A different approach to the problem of cooling a deployed high temperature superconducting coil is to use selective absorber and emitter coatings over a greater area of illumination. For example, by providing a mesh or Mylar sheet that has a desired absorptivity to emissivity ratio across the length of the central region inside the torus, as shown in Figure 1, and by orienting that sheet perpendicular to the sun, the area of illumination compared to the radiating area is significantly decreased.

The desirability of adding this sheet to the design may be proven by examining the energy balance between the absorption of solar energy and the reradiation of that energy. The total power absorbed by a body is governed by the following relation:

$$P_{in} = S\alpha A_1 \quad (24)$$

where  $S$  = the solar power flux (watts/cm<sup>2</sup>)  
 $\alpha$  = the absorptivity  
 $A_1$  = the illuminated area

The total power radiated away from a body is found as follows:

$$P_{out} = \sigma \epsilon A_2 T_e^4 \quad (25)$$

where  $\sigma$  = the Stefan-Boltzman constant  
 $= 5.67 \times 10^{-12}$  watts/cm<sup>2</sup>-K<sup>4</sup>  
 $\epsilon$  = the emissivity  
 $A_2$  = the emitting area  
 $T_e$  = the temperature of the body

If it is now assumed that the major radius of the torus is 2036 meters and the minor radius is 0.5 meter, the illuminated area and the emitting area can be determined. First, the illuminated area is simply the product of the major diameter and the minor diameter, as indicated below:

$$A_1 = (2R)(2r) \quad (26)$$

This is calculated to be 4072 m<sup>2</sup> with the example we have been using. The emitting area is next found as follows:

$$A_2 = [(2\pi R)(2\pi r)] + [2\pi(R-r)^2] \quad (27)$$

This accounts for the area gained from the inner sheet of foil, and is calculated to be  $2.61 \times 10^7$  m<sup>2</sup> in this case. Now, by setting equation 24 equal to equation 25, the following relation is obtained:

$$T_e = \left( \frac{S\alpha A_1}{\sigma \epsilon A_2} \right)^{\frac{1}{4}} \quad (28)$$

Finally, if the same absorptivity to emissivity ratio of  $6.17 \times 10^{-2}$  is used, and if the solar constant is estimated to be that at Earth orbit, 1350 watts/m<sup>2</sup>,<sup>12</sup> then the equilibrium temperature can be found using equation 26. This reveals that an equilibrium temperature of 21.9 K is achieved, which is well below the required equilibrium temperature of approximately 77 K.

Thus, it appears that a viable alternative to using mechanical cooling exists. However, numerous design problems are presented by this configuration. First, a total area of  $1.3 \times 10^7$  m<sup>2</sup> of foil would be required as the sheet material, and the deployment of such a foil would not be trivial. Second, this foil may present a mass penalty, but this would need to be evaluated in light of the enormous masses (and energies) required by mechanical cooling systems. A third problem is that the orientation of the torus would need to be maintained. This might be difficult due to variations in the intensity of the magnetic



field, but is certainly achievable with present-day orientation and stabilization technologies developed for satellites. Fourth, it should be noted that a temperature gradient would exist across the area of the web or foil, with the coldest point being at or near the middle. This might require increasing the rate of thermal conduction in the web or foil. If a hollow web was used, this problem could be solved by allowing a gas to circulate through the matrix by forced convection. Only a small quantity of gas would be required here. Alternatively, the entire configuration could be allowed to cool naturally, as long as the necessary time for such cooling is within practical limits on such a mission. This entirely self-cooled system, with its stringent requirement on orientation, may not be practical with many designs that have already been proposed for a Mars mission. However, it does indicate the engineering possibility of dispensing with mechanical cooling entirely if the mission design can be approached with a free hand.

### **Shield and Spaceship Configuration**

A previously published design for a manned Mars expedition took into account special considerations, such as the requirement of producing artificial gravity by rotation, and resulted in a specific ship geometry. This geometry has been adapted to incorporate a high temperature superconducting coil magnetic shield, as shown in figure 2. This geometry displays a coil of approximately a figure eight configuration in deployed state. One important design criteria is the production of a magnetic field to protect the crew quarters, and thus a distribution of the coil wires around the exterior of those areas those areas is essential such that the magnetic field in the interior of the living quarters are substantially canceled out.

### **Using the Deployed Coil as a Magnetic Sail**

It was first suggested by Engleberger<sup>24</sup> that the interaction between a shipboard magnetic field and the earth's magnetic field could provide a small amount of propulsion. Since this propulsive force will increase as the ship's magnetic field increases, it is evident from the magnitude of the magnetic moments discussed here that it is possible to consider this in the present case. However, detailed calculation shows that with a assumed magnetic moment of  $1.5 \times 10^6$  amps·m<sup>2</sup> (the prototype payload scale) 20 millionths of a pound of thrust can be obtained in this fashion. More interestingly, it has also been suggested that thrust may also be obtained due to the change in momentum of the repelled protons. Zubrin has estimated that accelerations on the order of 0.01 m/s<sup>2</sup> may be obtained.<sup>25</sup> Since, in either case, what is needed is a large magnetic moment and since this is what is produced by the method described here, it is evident that both of these concepts might be tested using the same payload as that

# Fig. 2

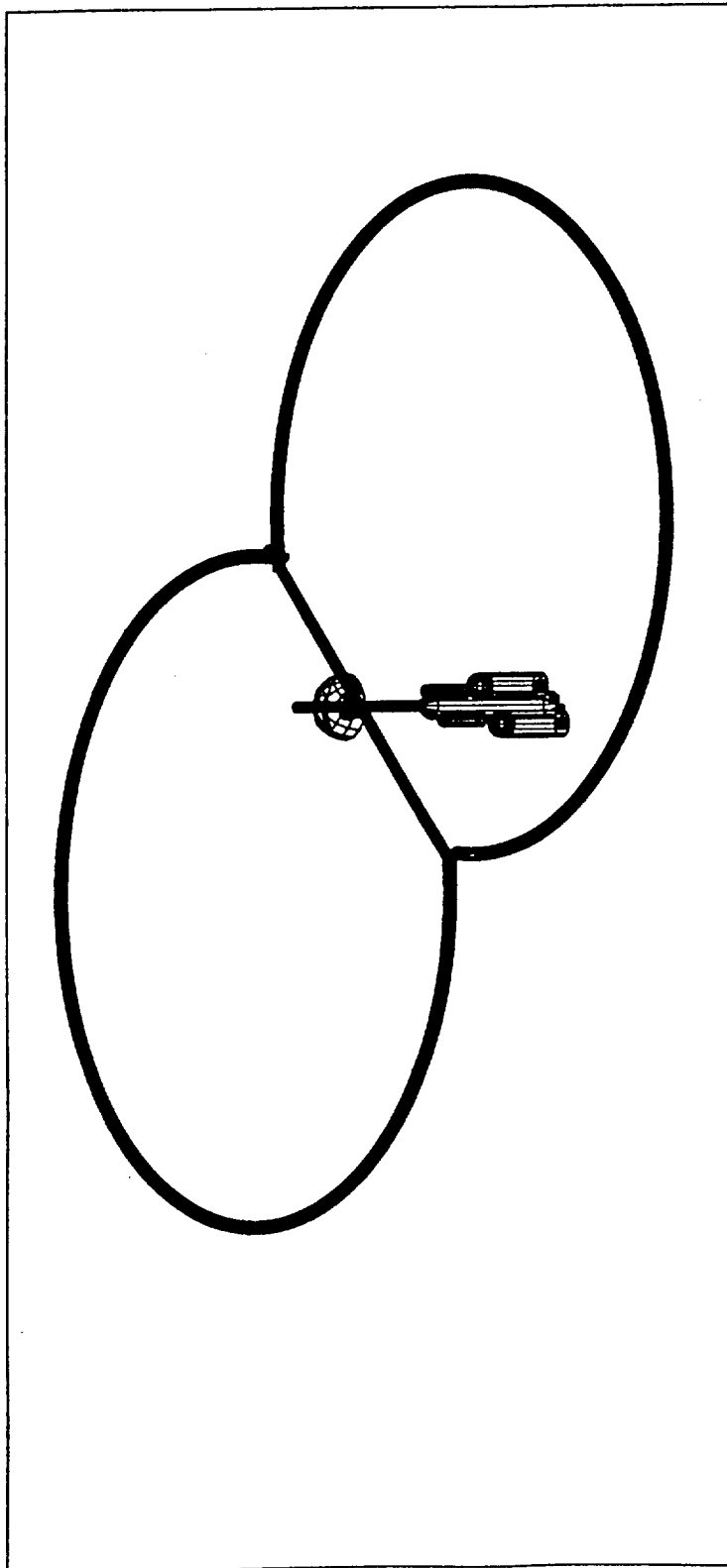


Fig. 2 Proposed ship geometry for manned Mars mission using the General rocket propulsion design of J. M. Butler, Jr., "Mars Mission and Bases - A Recent Look", Proc. of the Eighteenth Electronics and Aerospace Conference (EASCON), IEEE, New York, Catalogue Number BSCN 8213-7, pp. 211-222.

Duke University  
ME160 Senior Design  
In the  
NASA USRA Advanced  
Design Program  
1993

## DHTSC

Deployed High Temperature  
Superconducting Coil

SIZE	FSCH NO.	DWG NO.	REV
A		ID No. 1-100-105	5
NOT TO SCALE		SHEET 1 of 1	

needed to test radiation shielding. Furthermore, an analysis of the amount of drag to be experienced in orbit shows that for orbits at approximately 200 miles, the atmospheric drag is, typically, also on the order of 20 millionths of a pound. Thus, the concept of compensating for atmospheric drag by means of magnetic repulsion appears to be viable.<sup>26</sup>

### Design of a Prototype System

Efforts have been focused in the current design cycle on defining the criteria for constructing a prototype system to test the magnetic shielding concept. A small, self-contained payload is envisioned, one which is capable of being launched piggyback on another mission into geosynchronous orbit. Prototype design includes the following areas:

- torus deployment system
- sensing technologies
- command, control, and communications technologies
- energy control technologies
- thermal considerations
- flexible superconducting wire

An important consideration is scaling, i.e. the sizing of the deployed coil. Detailed calculations on this matter using the equations given above have shown that with currently available high temperature superconducting wires it should be possible to use a deployed coil having a radius of under ten meters to shield a 10 centimeter zone around the torus major diameter against 50 MEV protons. The total system mass goal is 200 kg.

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## APPENDIX

### MAGNETIC, ELECTROSTATIC, AND PLASMA SHIELDING OF SPACECRAFT - A BIBLIOGRAPHY

A compilation is given of references to methods of shielding spacecraft from solar and galactic radiation by means other than mass shielding. Both computer and manual searching has been used to ensure inclusion of older reference materials and this compilation covers government reports, journal articles, and patents. Literature on magnetometers as well as magnetic field testing facilities and equipment are not covered. Other topics of related interest, but not covered herein, include: magnetic sails, radiation protection standards and practices, and magnetic fields in space.

The employment of superconductors has been central to most concepts for the protection of spacecraft using magnetic fields; until recently, however, the superconducting materials available were not conducive to use. With the development of high temperature superconductors, new active shielding studies have been undertaken and major design advantages appear to be possible. A review of literature on shielding concepts reveals designs ranging from shipboard coils to deployed systems. However, no survey of this field would be complete without referencing Carl Störmer's pioneering book, *The Polar Aurora*, published in 1955, which although not directly concerned with spacecraft shielding provides the mathematical basis for virtually all subsequent magnetic radiation shielding work.

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One highlight of the semester class work under the NASA/USRA Advanced Design Program was a teleconference with our NASA mentor, Don Carson, at Goddard Space Flight Center. The class is shown interacting during this meeting.



